Global analysis of $B \to PP$, PV charmless decays with QCD factorization*

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Abstract

The global analysis of $B \to PP$, PV charmless decays with QCD factorization (QCDF) is presented. The predictions of QCDF are in good agreement with experiments. The best fitted CKM angel γ is around 79°. The predicted branching ratios of $B \to \pi^0\pi^0$, ωK^+, $\omega\pi^+$, π^+K^{*0} etc. are also in good agreement with new data of BaBar and Belle.

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I. INTRODUCTION

The charmless two-body B decays are very important for extracting CKM angles α, γ and for testing QCD. Up to now, BaBar and Belle have accumulated large set of data. It is highly interesting to analysis these data by using different theories and compare the data with theoretical predictions. QCD factorization [1] has been used to analysis $B \to PP$, PV charmless decay data [2, 3] (here P denotes pseudoscalar meson, V vector meson). With the data at that time, the theoretical results prefer a larger CKM angle γ. The QCD factorization (QCDF) predictions for some $B \to PV$ channels are only marginally consistent with the experimental data. Notice that the QCDF predictions contain large numerical uncertainties due to the CKM matrix elements, form factors, and annihilation parameters. Furthermore, the uncertainties of various decay channels are strongly correlated to each other. So we are stimulated to do a global analysis to check the consistency between the QCDF predictions and the experimental data. Beneke *et al.* [4] have done a gloabl analysis for $B \to PP$, including $\pi\pi$, πK modes with QCDF approach. The results show a satisfactory agreement between QCDF predictions and data for $B \to PP$ branching fractions. But their fitted CKM angle $\gamma \sim 90°$ which is not consistent with the standard CKM fit [5]: $37° \leq \gamma \leq 80°$. Now BaBar and Belle have a lot of data on $B \to PV$. It is necessary to do the global fit to $B \to PP$ and PV at the same time. We have done it and found that QCDF can fit all data on $B \to PP$, PV. The fitted angle $\gamma \sim 79°$ which is consistent with the standard CKM global fit. We also have new predictions on $B \to \pi^0\pi^0$, K^+K^-, π^+K^{*0}, $\omega\pi^+$, ωK^+.

My talk is organized as follows: in Section II, I give general remarks on QCD factorization. Section III is devoted to the global analysis on $B \to PP$, PV decays. In Section IV, I give the summary and conclusion.

II. GENERAL REMARKS ON QCD FACTORIZATION

The low energy effective Hamiltonian for $|B| = 1$ is

$$\begin{aligned}\mathcal{H}_{eff} &= \frac{G_F}{\sqrt{2}} \sum_{q=u,c} v_q \Big\{ C_1(\mu) Q_1^q(\mu) + C_2(\mu) Q_2^q(\mu) \\ &+ \sum_{k=3}^{10} C_k(\mu) Q_k(\mu) \Big\} + \text{H.c.}, \qquad (1)\end{aligned}$$

The decay amplitude for $B \to M_1 M_2$ is

$$\mathcal{A}(B \to M_1 M_2) = \frac{G_F}{\sqrt{2}} \sum_i \sum_q C_i(\mu) \langle M_1 M_2 | Q_i(\mu) | B \rangle, \tag{2}$$

The Wilson coefficients $C_i(\mu)$ include short distance effects above the scale $\mathcal{O}(m_b)$ and are perturbatively calculable. The long distance effects (contributions from the scale below $\mathcal{O}(m_b)$) are included in the hadronic matrix elements $\langle M_1 M_2 | Q_i(\mu) | B \rangle$.

For naive factorization (BSW),

$$\langle M_1 M_2 | Q_i(\mu) | B \rangle \sim \underbrace{\langle M_1 | J_1 | 0 \rangle}_{\swarrow \atop \text{decay constant}} \underbrace{\langle M_2 | J_2 | B \rangle}_{\searrow \atop \text{form factor}} \tag{3}$$

There are no renormalization scheme and scale dependences. So the corresponding dependences of $C_i(\mu)$ connot be canceled and the "non-factorizable" contributions cannot be accounted for.

In 1999, Beneke *et al.* [1] proposed a new factorization scheme based on QCD. That is so-called QCD factorization (QCDF). In this scheme, in the heavy quark limit,

$$\begin{aligned} \langle M_1 M_2 | O_i | B \rangle &= F_j^{B \to M_2}(q^2) \int_0^1 dx T_i^I(x) \Phi_{M_1}(x) + (M_1 \leftrightarrow M_2) \\ &+ \sum_j \int_0^1 d\xi \int_0^1 dx \int_0^1 dy T_{ij}^{II}(\xi, x, y) \Phi_B(\xi) \Phi_{M_1}(x) \Phi_{M_2}(y) + \mathcal{O}(\Lambda_{QCD}/m_b) \end{aligned} \tag{4}$$

where $T_i^{I,II}$ denote hard scattering kernels which are calculable order by order in perturbation theory and include short distance effects. The long distance effects are included in decay constants, form factors and ling-cone distribution amplitudes. M_1 is a light meson or a charmonium state. M_2 (containts the spectator quark in B meson) is any light or heavy meson. If M_2 is heavy (for example, D meson), the second line in the Eq.(4) is $1/m_b$ suppressed.

General observation:

- At the zeroth order of α_s, it reduces to naive factorization
- At the higer order, the corrections can be computed systematically
- The renormalization scheme and scale dependence of $\langle Q_i \rangle$ is restored. In the heavy quark limit, the "non-factorization" contributions is calculable perturbatively. It does not need to introduce $N_c^{\rm eff}$

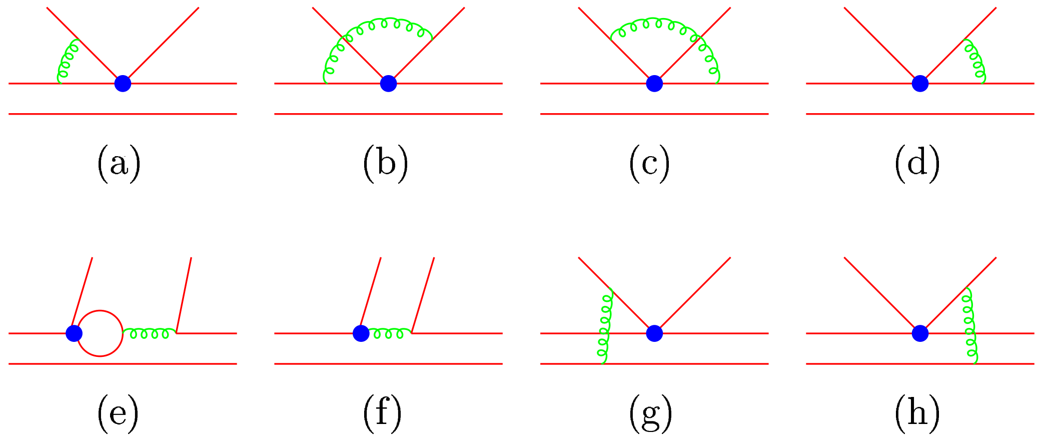


FIG. 1: $T^{I,II}$ at $\mathcal{O}(\alpha_s)$. The upward quark lines denote the ejected meson M_1

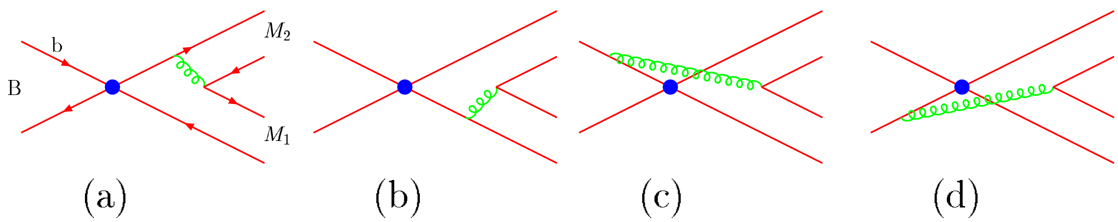


FIG. 2: annihilation contributions

- In heavy quark limit, strong phases arise solely from vertex and penguin corrections, so are at $\mathcal{O}(\alpha_s)$. That means that *strong phases are α_s-suppressed.*

- Numerically, $\Lambda_{QCD}/m_b \sim \mathcal{O}(\alpha_s)$, so power corrections contribution to strong phases are also important. We do not have a systematic way to estimate power (Λ_{QCD}/m_b) corrections. Thus *the calculation of strong phase is not reliable. So CP asymmetry calculation is unreliable.*

- W-exchange & W-annihilation diagrams are $1/m_b$ suppressed

- No long distance interactions between M_1 and (BM_2)

- T^I includes:
  α_s^0 : tree diagram
  α_s : non-factorizable gluon exchange
  vertex corrections (Fig.1(a)-(d))
  penguin corrections (Fig.1(e)-(f))
  $\vdots$

- T^{II} includes:
  α_s : hard spectator scattering (Fig.1(g)-(h))
  $\vdots$

Superficially, $\Lambda_{QCD}/m_b \sim 1/15$ is a small number, But in some cases, such power suppression fails numerically. For example

$$\langle Q_6 \rangle_{\mathrm{F}} = -2 \sum_{q'} \langle P_1 | (\bar{q} q')_{S-P} | 0 \rangle \langle P_2 | (\bar{q}' b)_{S+P} | B \rangle \tag{5}$$

is always multiplied by a formally power suppressed but chirally enhanced factor $r_\chi = 2\mu_P/m_b$ ($\mu_p = m_P^2/(m_1+m_2)$, m_i are current quark masses). In the heavy quark limit, $m_b \to \infty$, $r_\chi \to 0$. But for $m_b \sim 5$GeV, $r_\chi \sim \mathcal{O}(1)$, no $1/m_b$ suppression. So we should consider the chirally enhanced power corrections. For example, in $B \to \pi K$, penguin is important. Dominant contribution to the amplitude $\sim a_4 + a_6 r_\chi$, ($a_4 \sim a_6 r_\chi$). So chirally enhanced power correction term $a_6 r_\chi$ cannot be neglected.

Possible sources of power corrections:

- high twist wave functions;
- quark transverse momentum $k_\perp$;
- annihilation topology diagrams.

When we include chirally enhanced power corrections, the infrared (including soft and collinear) divergences for vertex corrections cancel only if $\Phi_\sigma(x)$ is symmetric, i.e. $\Phi_\sigma(x) = \Phi_\sigma(1-x)$ (Φ_σ, Φ_p are twist-3 wave functions). But even $\Phi_\sigma(x) = \Phi_\sigma(1-x)$, there is still logarithmic divergence for hard spectator scattering and annihilation topology. It violates factorization.

$$\begin{aligned} &X_{H,A} = \int_0^1 \frac{dx}{x} = \ln \frac{m_B}{\Lambda_h}(1+\rho_{H,A} e^{i\phi_{H,A}}) \\ &\Lambda_h \sim 0.5\text{GeV}, \quad 0 < \rho_{H,A} < 1, \quad 0^\circ \leq \phi_{H,A} < 360^\circ \end{aligned} \tag{6}$$

Other power corrections maybe unimportant based on Renormalon Calculus estimation [6].

III. GLOBAL ANALYSIS OF $B \to PP$, PV

The decay amplitudes of $B \to PP$, PV can be written as

$$\mathcal{A}(B\to M_1M_2) = \frac{G_F}{\sqrt{2}}\sum_i v_q a_i^p \langle M_1|J_1|0\rangle\langle M_2|J_2|B\rangle + \frac{G_F}{\sqrt{2}} f_B f_{M_1} f_{M_2}\sum_i v_q b_i \tag{7}$$

where $b_i = b_i(X_A, \alpha_s) = \alpha_s f(X_A)$ is related to the contributions of annihilation topology.

We use CKMFitter package [7] developed for global analysis of $B \to PP$ and enlarged it to include $B \to PV$. The RFit scheme is implemented for statistical treatment, assuming the experimental errors to be purely Gaussian, while *quantites that cannot be computed precisely are bound to remain within their predefined allowed ranges.*

The input parameters are as follows:

1. two-parton light-cone distribution amplitudes.

- for pseudoscalar meson

$$\begin{aligned}&\langle P(k)|\bar{q}_\alpha(z_2)q_\beta(z_1)|0\rangle\\ =& \frac{if_P}{4}\int_0^1 dx e^{i(xk\cdot z_2+\bar{x}k\cdot z_1)}\Big\{\not{k}\gamma_5\Phi_P(x) \ -\mu_P\gamma_5\Big[\Phi_P^p(x)-\sigma_{\mu\nu}k^\mu z^\nu\frac{\Phi_P^\sigma(x)}{6}\Big]\Big\}_{\beta\alpha}\end{aligned} \tag{8}$$

  where $z = z_1 - z_2$.

- for longitudinally polarized vector meson

$$\langle V(k,\lambda)|\bar{q}_\alpha(z_2)q_\beta(z_1)|0\rangle = -\frac{if_V}{4}m_V\int_0^1 dx\, e^{i(xk\cdot z_2+\bar{x}k\cdot z_1)}\Big\{k_\mu\frac{\varepsilon_\lambda^*\cdot z}{k\cdot z}\Phi_\parallel^V(x)\Big\}_{\beta\alpha}, \tag{9}$$

  for vector meson, the contributions of the twist-3 LCDAs are doubly suppressed, so can be safely disregarded.

- In order to reduce the number of input parameters, we use the asymptotic light-cone distribution amplitudes for final light mesons instead of Gegenbauer polynomials.

$$\Phi_P(x) = 6x\bar{x}, \quad \Phi_P^\sigma(x) = 6x\bar{x}, \quad \Phi_P^p(x) = 1, \quad \Phi_\parallel^V(x) = 6x\bar{x}, \tag{10}$$

- for B meson, its wave function appears only in the contributions of hard spectator scattering [4]

$$\int_0^1 \frac{d\xi}{\xi}\Phi_B(\xi) \equiv \frac{m_B}{\lambda_B}, \qquad \lambda_B = (350\pm150)\,\text{MeV}, \tag{11}$$

2. chirally enhanced factor & annihilation-related parameters

$$
\begin{aligned}
r_\chi^\pi \simeq r_\chi^\eta \simeq r_\chi^K &= \frac{2m_K^2}{m_s m_b}, \quad m_b(m_b) = 4.2\,\mathrm{GeV}, \quad m_s(2\,\mathrm{GeV}) = (110\pm 25)\,\mathrm{MeV}, \\
X_{H,A}^{PP} = \ln\frac{m_B}{\Lambda_h}(1+\rho_{H,A}^{PP} e^{i\phi_{H,A}^{PP}}), &\qquad X_{H,A}^{PV} = \ln\frac{m_B}{\Lambda_h}(1+\rho_{H,A}^{PV} e^{i\phi_{H,A}^{PV}})
\end{aligned} \tag{12}
$$

(note: X_H, X_A for $B\to PP$ are different for $B\to PV$)

3. Decay constants and form factors

$$
\begin{aligned}
&f_\pi = 131\,\mathrm{MeV},\ f_K = 160\,\mathrm{MeV}, \quad f_{K^*} = 214\,\mathrm{MeV},\ f_\rho = 210\,\mathrm{MeV}, \\
&f_\omega = 195\,\mathrm{MeV},\ f_\phi = 233\,\mathrm{MeV}, \quad f_B = 180\,\mathrm{MeV}, \quad \phi = 39.3^\circ, \\
&f_q = 1.07 f_\pi, \quad f_s = (1.34\pm 0.06) f_\pi,\ f_\eta^q = f_q \cos\phi, \quad f_\eta^q = -f_s \sin\phi, \\
&F_{0,1}^{B\to\pi}(0) = 0.28\pm 0.05,\ A_0^{B\to\rho}(0) = 0.30\pm 0.05,\ R_{\pi K} \equiv \tfrac{f_\pi F^{B\to K}}{f_K F^{B\to\pi}} = 0.9\pm 0.1, \\
&A_0^{B\to\omega}(0) = A_0^{B\to\rho}(0), \qquad F_{0,1}^{B\to\eta} = F_{0,1}^{B\to\pi}\left(\tfrac{\cos\theta_8}{\sqrt{6}} - \tfrac{\sin\theta_0}{\sqrt{3}}\right), \\
&f_q \to |\eta_q\rangle = \tfrac{|u\bar u\rangle + |d\bar d\rangle}{\sqrt 2},\ \langle 0|s\gamma_5 \bar s|\eta\rangle = -i\tfrac{m_\eta^2}{2m_s}\left(f_\eta^s - f_\eta^u\right)\ \theta_8 = \phi - \arctan(\sqrt{2} f_q/f_s), \\
&f_s \to |\eta_s\rangle = |s\bar s\rangle, \quad \tfrac{\langle 0|u\gamma_5 \bar u|\eta\rangle}{\langle 0|s\gamma_5 \bar s|\eta\rangle} = \tfrac{f_\eta^u}{f_\eta^s}, \qquad \theta_0 = \phi - \arctan(\sqrt{2} f_s/f_q),
\end{aligned} \tag{13}
$$

4. CKM parameters

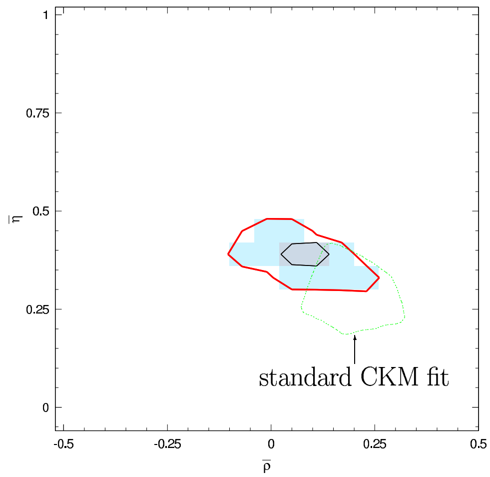
We use Wolfenstein parameterization for the CKM matrix and take

$$
A = 0.835, \qquad \lambda = 0.22, \qquad |V_{ub}| = 3.49\pm 0.24_{\mathrm{exp}}\pm 0.55_{\mathrm{theo}}, \tag{14}
$$

and use the measured branching fractions listed in Table.I as input. We did not use the branching ratios in Table.II as input. The reason is that the errors of the data are large and the glue content of $\eta^{(\prime)}$-meson cannot be treated neatly. Detailed discussion can be found in our published paper [8]. For experimental constraints of CP asymmetries, the corresponding QCDF predictions are not reliable. Thus we do not use measured CP asymmetries as input in our global fit.

For $B\to\pi\pi$, πK, the fit is sensitive to $|V_{ub}|$, $\gamma\,(\rho,\eta)$, $F^{B\to\pi}$, $F^{B\to K}$, X_A, f_B/λ_B, m_s. Including seven $B\to PV$ decay channels, only $A_0^{B\to\rho}$, X_A^{PV} are newly involved sensitive parameters. So including $B\to PV$ we shall have more stringent test of QCDF. Our best fit of $\gamma\sim 79^\circ$ (see Figure.3) which is consistent with recent fit results $37^\circ<\gamma<80^\circ$ [7]. The best fitted results are listed in Table.III.

The confidence levels of the fitted branching ratios are presented in Figure.4. From Figure.4 we can see that



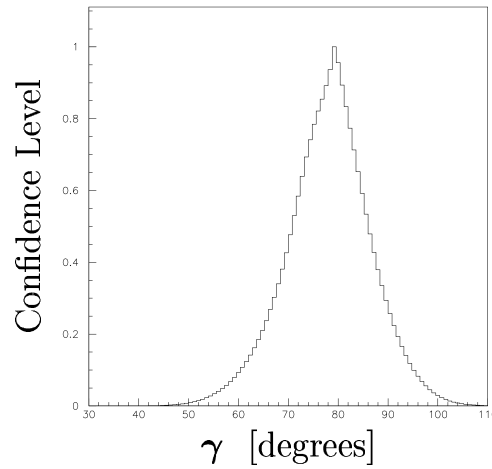


FIG. 3: left: the contours indicate ≥90% C.L.& ≥5% C.L. right: C.L. of angle γ.

- For $B \to \pi^0\pi^0$, the best fit is around 1×10^{-6} while the BaBar and Belle averaged measurement is $(1.90\pm0.49)\times10^{-6}$.
- For $B^+ \to \omega K^+$, the best fit is 6.25×10^{-6} while the Belle measurement is $(9.2^{+2.6}_{-2.3}\pm1.0)\times10^{-6}$, and the CLEO measurement is $< 8\times10^{-6}$.
- For $B^+ \to \omega\pi^+$, the best fit is 6.66×10^{-6} while the BaBar measurement is $(6.6^{+2.1}_{-1.8}\pm0.7)\times10^{-6}$, and the Belle measurement is $< 8.2\times10^{-6}$.
- For $B^+ \to \pi^+K^{*0}$, the best fit $\sim 10\times10^{-6}$ while the BaBar preliminary measurement reported at LP03 is $(10.3\pm1.2^{+1.0}_{-2.7})\times10^{-6}$.

On the whole, our global fit is successful.

IV. SUMMARY & CONCLUSION

- QCD factorization is a promising method for charmless two-body B decays, which are cruical for the determination of the unitarity triangle.
- We enlarged the CKMFitter package to include $B \to PV$ charmless decay channels and did a global analysis. It is shown that the QCDF predictions are basically in good agreement with the experiments.
- We obtain $\gamma \sim 79°$, consistent with the CKM global fit.

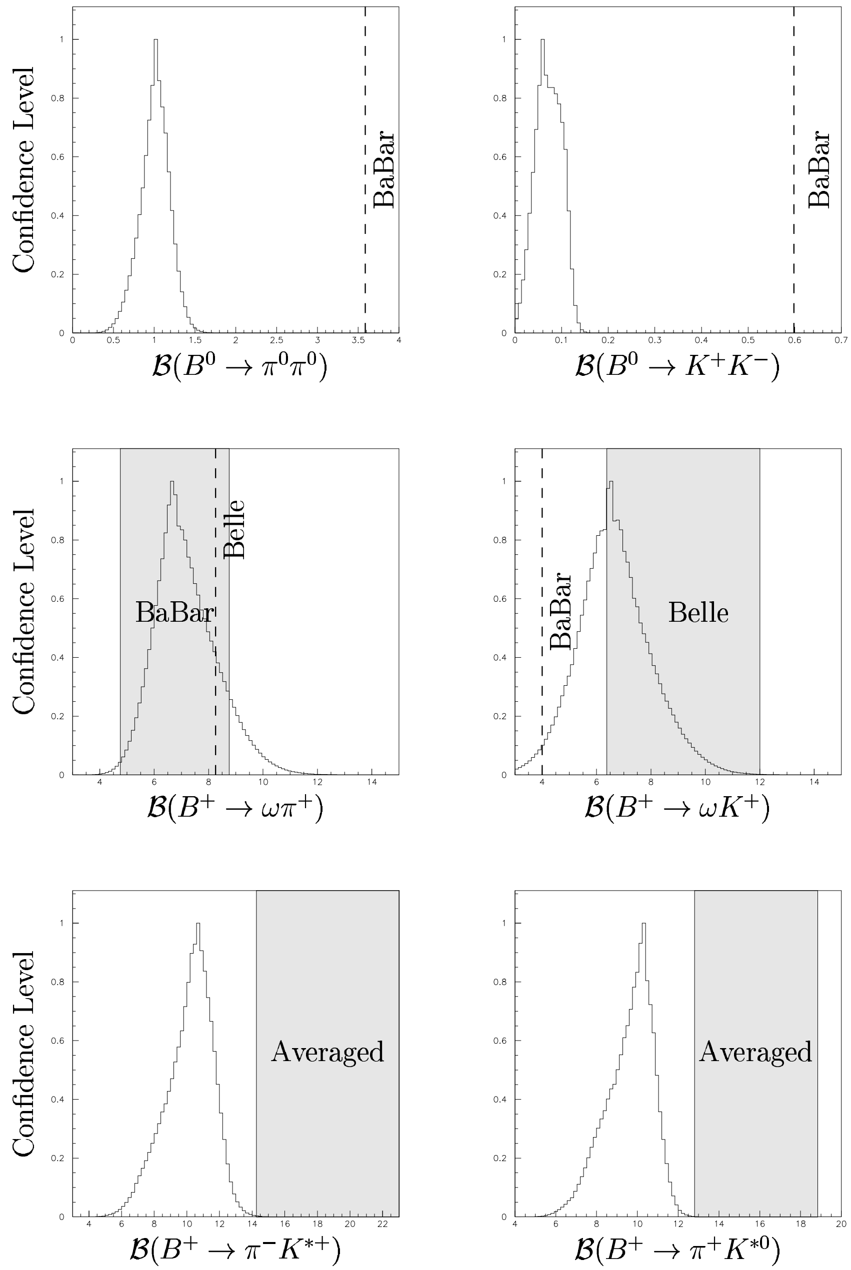


FIG. 4: The confidence levels of the fitted branching fractions (in the unit of 10^{-6}).

- For $B \to \pi^0\pi^0$, the best fit is around $1{\times}10^{-6}$ while the BaBar and Belle averaged measurement is $(1.90{\pm}0.49){\times}10^{-6}$.

- For $B^+ \to \omega K^+$, the best fit is $6.25{\times}10^{-6}$ while the Belle measurement is $(9.2^{+2.6}_{-2.3}{\pm}1.0){\times}10^{-6}$, and the CLEO measurement is $< 8{\times}10^{-6}$.

- For $B^+ \to \omega\pi^+$, the best fit is $6.66{\times}10^{-6}$ while the BaBar measurement is $(6.6^{+2.1}_{-1.8}{\pm}0.7){\times}10^{-6}$, and the Belle measurement is $< 8.2{\times}10^{-6}$.

- For $B^+ \to \pi^+ K^{*0}$, the best fit $\sim 10{\times}10^{-6}$ while the BaBar preliminary measurement reported at LP03 is $(10.3{\pm}1.2^{+1.0}_{-2.7}){\times}10^{-6}$.

The results are already published in [8]. I thank Drs. Junfeng Sun, Deshan Yang and Guohuai Zhu for their collaboration.

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TABLE I: Experimental data used in the global fit

$\mathcal{B}r\times10^6$	CLEO	BaBar	Belle	weighted average
$B^0\to\pi^+\pi^-$	$4.3^{+1.6}_{-1.4}\pm0.5$	$4.7\pm0.6\pm0.2$	$5.4\pm1.2\pm0.5$	4.77 ± 0.54
$B^+\to\pi^+\pi^0$	$5.4^{+2.1}_{-2.0}\pm1.5$	$5.5^{+1.0}_{-0.9}\pm0.6$	$7.4^{+2.3}_{-2.2}\pm0.9$	5.78 ± 0.95
$B^0\to K^+\pi^-$	$17.2^{+2.5}_{-2.4}\pm1.2$	$17.9\pm0.9\pm0.7$	$22.5\pm1.9\pm1.8$	18.5 ± 1.0
$B^+\to K^+\pi^0$	$11.6^{+3.0+1.4}_{-2.7-1.3}$	$12.8^{+1.2}_{-1.1}\pm1.0$	$13.0^{+2.5}_{-2.4}\pm1.3$	12.7 ± 1.2
$B^+\to K^0\pi^+$	$18.2^{+4.6}_{-4.0}\pm1.6$	$17.5^{+1.8}_{-1.7}\pm1.3$	$19.4^{+3.1}_{-3.0}\pm1.6$	18.1 ± 1.7
$B^0\to K^0\pi^0$	$14.6^{+5.9+2.4}_{-5.1-3.3}$	$10.4\pm1.5\pm0.8$	$8.0^{+3.3}_{-3.1}\pm1.6$	10.2 ± 1.5
$B^+\to\eta\pi^+$	< 5.7	< 5.2	$5.3^{+2.0}_{-1.7}\,(< 8.2)$	< 5.2
$B^0\to\pi^\pm\rho^\mp$	$27.6^{+8.4}_{-7.4}\pm4.2$	$28.9\pm5.4\pm4.3$	$20.8^{+6.0+2.8}_{-6.3-3.1}$	25.4 ± 4.3
$B^+\to\pi^+\rho^0$	$10.4^{+3.3}_{-3.4}\pm2.1$	< 39	$8.0^{+2.3}_{-2.0}\pm0.7$	8.6 ± 2.0
$B^0\to K^+\rho^-$	$16.0^{+7.6}_{-6.4}\pm2.8$		$11.2^{+5.9+1.9}_{-5.6-1.8}$	13.1 ± 4.7
$B^+\to\phi K^+$	$5.5^{+2.1}_{-1.8}\pm0.6$	$9.2\pm1.0\pm0.8$	$10.7\pm1.0^{+0.9}_{-1.6}$	8.9 ± 1.0
$B^0\to\phi K^0$	$5.4^{+3.7}_{-2.7}\pm0.7$	$8.7^{+1.7}_{-1.5}\pm0.9$	$10.0^{+1.9+0.9}_{-1.7-1.3}$	8.6 ± 1.3
$B^+\to\eta\rho^+$	< 10		< 6.2	< 6.2
$B^0\to\omega K^0$	< 21	$5.9^{+1.7}_{-1.5}\pm0.9$		5.9 ± 1.9

TABLE II: data not used in the global fit

$\mathcal{B}r\times10^6$	CLEO	BaBar	Belle	weighted average
$B^+\to\eta K^+$	< 6.9	< 6.4	$5.2^{+1.7}_{-1.5}\,(< 7.7)$	< 6.4
$B^+\to\pi^+K^{*0}$	< 16	$15.5\pm3.4\pm1.8$	$16.2^{+4.1}_{-3.8}\pm2.4$	15.8 ± 3.0
$B^0\to\pi^-K^{*+}$	$16^{+6}_{-5}\pm2$		$26.0\pm8.3\pm3.5$	19.0 ± 4.9
$B^+\to\eta K^{*+}$	$26.4^{+9.6}_{-8.2}\pm3.3$	$22.1^{+11.1}_{-9.2}\pm3.3$	$26.5^{+7.8}_{-7.0}\pm3.0$	25.4 ± 5.3
$B^0\to\eta K^{*0}$	$13.8^{+5.5}_{-4.6}\pm1.6$	$19.8^{+6.5}_{-5.6}\pm1.7$	$16.5^{+4.6}_{-4.2}\pm1.2$	16.4 ± 3.0
$B^+\to\omega K^+$	< 8	< 4	$9.2^{+2.6}_{-2.3}\pm1.0$	
$B^+\to\omega\pi^+$	$11.3^{+3.3}_{-2.9}\pm1.5$	$6.6^{+2.1}_{-1.8}\pm0.7$	< 8.2	

TABLE III: Fit1 and Fit2 mean the best fit value with and without the contribution of the chirally enhanced hard spectator and annihilation topology, respectively.

modes	Exp.	Fit1	Fit2
$B^0 \to \pi^+\pi^-$	4.77±0.54	4.82	5.68
$B^+ \to \pi^+\pi^0$	5.78±0.95	5.35	3.25
$B^0 \to K^+\pi^-$	18.5±1.0	19.0	18.8
$B^+ \to K^+\pi^0$	12.7±1.2	11.4	12.6
$B^+ \to K^0\pi^+$	18.1±1.7	20.1	20.2
$B^0 \to K^0\pi^0$	10.2±1.5	8.2	7.3
$B^+ \to \eta\pi^+$	< 5.2	2.8	1.8
$B^0 \to \pi^\pm\rho^\mp$	25.4±4.3	26.7	29.5
$B^+ \to \pi^+\rho^0$	8.6±2.0	8.9	8.5
$B^0 \to K^+\rho^-$	13.1±4.7	12.1	5.1
$B^+ \to \phi K^+$	8.9±1.0	8.9	7.1
$B^0 \to \phi K^0$	8.6±1.3	8.4	6.7
$B^+ \to \eta\rho^+$	< 6.2	4.6	3.8
$B^0 \to \omega K^0$	5.9±1.9	6.3	1.2